PRINT: ISSN 0976-6901 ONLINE: ISSN 2456-6543
J Biodiversity, 5(1,2): 11-32(2014)
DOI: 10.31901/24566543.2014/05.1-2.02

Hydrological Responses at Regional Scale to Landscape Dynamics

T.V. Ramachandra

Energy and Wetlands Research Group, Centre for Ecological Sciences
Indian Institute of Science, Bangalore 560 012, India
Fax: 91-080-23601428 / 23600085 / 23600683 [CES TVR]
E-mail: cestvr@ces.iisc.ernet.in, energy@ces.iisc.ernet.in

KEYWORDS Land Use. Land Cover. Western Ghats. Tropical Ecosystems. Stream Flow

ABSTRACT Western Ghats is the primary catchment for most of the rivers in peninsular India. Pristine forests in this region are rich in biodiversity and are being cleared due to unsound developmental activities. Rapid land-use changes have undermined the hydrological conditions, there by affecting all the components in the hydrological regime. The development programs based on ad-hoc decisions, is posing serious challenges in conserving fragile ecosystems. These changes have adversely affected the hydrological regime of river basins resulting in diminished river / stream flows. This necessitates conservation of ecosystems in order to sustain the biodiversity, hydrology and ecology. In this situation, in order to resolve present problems and to avoid a future crisis, a comprehensive assessment of land use changes, its spatial distribution and its impact on hydrological regime was carried out to explore appropriate remedial methods for the sustainable utilization management of natural resources.

INTRODUCTION

Developing countries in the tropics are facing threats of rapid deforestation due to unplanned developmental activities based on adhoc approaches and also due to policies and laws that considers forest as national resource to be fully exploited. The land use changes, involving conversion of natural forests to other land uses; agriculture (enhanced grazing pressure and intensive cultivation practices) and plantation (widespread acacia and eucalyptus planting) have led to soil compaction, reduced infiltration, groundwater recharge and discharge, and rapid and excessive runoff (Ray et al. 2015; Scott and Lesch 1997; Sikka et al. 1998; Van Lill et al. 1980). The structural changes in the ecosystem due to land cover changes, will influence the functional aspects namely hydrology, bio-geo chemical cycles and nutrient cycling. These are evident in many regions in the form of conversion of perennial streams to seasonal and disappearance of water bodies leading to a serious water crisis. Thus, it is imperative to understand the causal factors responsible for changes in order to improve the hydrologic regime in a region. It has been observed that the hydrological variables are complexly related with the vegetation present in the catchment. The presence or absence of vegetation has a strong impact on the hydrological cycle. This requires understanding of hydrological components and its relation to the land use/land cover dynamics. The reactions or the results are termed hydrological response and depends on the interplay between climatic, geological and land use variables (Ramachandra et al. 2014a).

Hydrological responses can be understood by analysing land use changes using temporal remote sensing data and traditional approaches. Traditional approaches considers spatial variability by dividing a basin into smaller geographical units such as sub-basins, terrain-based units, land cover classes, or elevation zones on which hydrological model computations are made, and by aggregating the results to provide a simulation for the basin as a whole. Modelling is thus simplified because areas of the catchment within these units are assumed to behave similarly in terms of their hydrological response. Remote sensing and GIS techniques have been used to determine some of the model parameters. The main applications of remote sensing in hydrology are to, i) determine watershed geometry, drainage network and other map type information for hydrological models, ii) provide input data such as land use/land cover, soil moisture, surface temperature etc. GIS on the other hand allows for the combination of spatial data such as topography, soil maps and hydrologic variables such as rainfall distribution or soil moisture (Ramachandra et al. 2013c).

Land cover is the observed physical cover at a given location and time as might be seen on the ground or from remote sensing. This includes the vegetation (natural or planted) and human constructions (buildings etc.), which cover the Earth surface. Land use is, in part a description of function, the purpose for which the land is being used. Land use and cover changes are the result of many interacting processes. Each of these processes operates over a range of spatial, temporal, quantitative, or analytical dimension used to measure and study objects and processes. Land-use and land-cover are linked to climate and weather in complex ways (Ramachandra et al. 2012). Key links between changes in land cover and climate include the exchange of greenhouse gases (such as water vapour, carbon dioxide, methane, and nitrous oxide) between land surface and atmosphere, the radiation (both short and long wave) balance of land surface, the exchange of sensible heat between land surface and atmosphere. Artificial changes to the natural cycle of water have produced changes in aquatic, riparian, wetland habitats and agricultural landscape. These interferences have had both positive and negative impacts on the problems that they were intended to solve. Some of these activities have greatly constrained the degree of interactions between the river channel and the associated floodplain with catastrophic effects on biodiversity.

Land Use Changes and Its Effect on Hydrology

Human activities have been recognized as a major force shaping the biosphere (Karthick and Ramachandra 2007; Turner and Meyer 1994). In the 1980's, terrestrial ecosystems as carbon sources and sinks were highlighted and later the important contribution of local evapotranspiration to the water cycle-that is precipitation recycling-as a function of land use/land cover highlighted yet another considerable impact of land use/land cover change on the climate. A much broader range of impacts of land use/land cover change on ecosystem goods and services were further identified (Lambin et al. 2003). A most efficient way of capturing the spatial and temporal details is by remote sensing. Hydrological models coupled with remote sensing data can efficiently characterize temporal and spatial effects of land use changes on the ecology and hydrology. Earlier studies confirm the relationship among the watershed physical characteristics and the storm-based hydrologic indices indicated that the greatest impact of land management is found with statistically significant predictive models for indices of time base, response lag, and time of rise of hydrograph (Ramachandra et al. 2015; Bhat et al. 2007).

Remote Sensing and GIS Techniques in Hydrology

Remote sensing uses measurements of the electromagnetic spectrum to characterize the landscape or infer properties of it (Ramachandra et al. 2015; Schultz and Engman 2000; Schmugge et al. 2002). Satellite observations are available since the early 1970's and it is possible to relate trends such as vegetation cover densities to stream flow. The land cover maps derived by remote sensing are the basis of hydrologic response units for modelling. Geographic information System (GIS) helps in the spatial data analysis, integration of a combination of spatial data (such as soil, topography, hydrologic variables, etc.) and modelling (Schultz and Engman 2000). GIS deals with information about features that is referenced by a geographical location. These systems are capable of handling both locational data and attribute data about such features through database management system (DBMS).

Western Ghats

The Western Ghats comprise the mountain range that runs along the western coast of India, from the Vindhya-Satpura ranges in the north to the southern tip. This range intercepts the moisture laden winds of the southwest monsoon thereby determining the climate and vegetation of the southern peninsula. The steep gradients of altitude, aspect and rainfall make the region ecologically rich in flora and fauna. There is a great variety of vegetation all along the Ghats: scrub jungles, grassland along the lower altitudes, dry and moist deciduous forests, and semi-evergreen and evergreen forests. Out of the 13,500 species of flowering plants in India, 4500 are found in the Western Ghats and of these 742 are found in Sharavathi river basin (Ramachandra et al. 2004). Climax vegetation of the wet tract consists of *Cullenia, Persea, Diptercarpus, Diospyros* and *Memecylon*. The deciduous forest tract is dominated by *Terminalia, Lagerstroemia, Xylia, Tectona* and *Anogeissus*. The region also contains potentially valuable spices and fruits such as wild pepper varieties, cardamom, mango, jackfruit and other widely cultivated plants. There is an equal diversity of animal and bird life. Noticeable reptile fauna in the evergreen forests include burrowing snakes (uropeltids) (Gadgil and Meher-Homji 1990) and the king cobra and among amphibians, the limbless frog (caecilians). The Nilgiri *langur*, lion-tailed macaque, Nilgiri *tahr* and Malabar large spotted civet are some examples of endangered endemic mammals belonging to this area. Sharavathi river valley lies in the Central Western Ghats and represents an area of 2985 km^2. Sharavathi is a west flowing river originating at Ambuthirtha in Shimoga district and during its course, falls from a height of around 253 m at the famed Jog Falls. It flows through Honnavar and eventually into the Arabian Sea.

Karnataka Power Cooperation Limited (KPCL) has set up a dam at Linganamakki across Sharavathi in 1964 to harness electricity, which has divided the river basin into upstream and downstream. The construction of this dam has made considerable hydrological and ecological alterations in the river basin. The dam resulted in the submergence of wetlands and forest areas of unmeasured biodiversity. The effects are particularly seen in the upstream of the river basin where the dam submerged many villages and forests to give rise to small isolated islands. These island and surrounding areas have created niches for 150 species of birds, 145 species of butterflies and 180 species of beetles along with mammals such as spotted deer, barking deer, civet, leopard and the Indian *gaur.* The reservoir has provided further impetus to farmers and plantation agriculturists. Large tracts of forestlands have been cleared for paddy cultivation and plantation trees such as areca and acacia. Apart from these, vast tracts of natural vegetation has been cleared and replaced with monoculture plantations of *Acacia auriculiformis*, Eucalyptus sp. and *Tectona grandis*. As a result of these activities, there is evidence of changes in runoff and stream flow regimes. There are instances where wells have 'run dry' in the wet spots of the basin, mainly because percolation of rainwater into the ground has decreased due to deforestation. Studies are thus required to quantify the hydrological responses in order to gain an understanding of the effect of anthropogenic activities on the hydrological components and thus the vegetation of study area.

Objectives

The objectives of the study are:

i. Quantification of hydrologic components of Sharavathi River Basin, Western Ghats using Remote Sensing and GIS.
ii. Study the impact of land use/land cover changes on hydrologic components.

Study Area

Sharavathi river (Fig. 1) originates at Ambuteertha, near Kavaledurga in Tirthahalli *taluk.* It flows in a north-westerly direction and receives the Haridravathi on the right and Yenneholé on the left. Near the border of the district, it bends to the west and hurls down the *ghats* near Jog where it is harnessed for generating electricity. It discharges into the sea at Honnavar in Uttara Kannada (Fig. 2). Its total length is 128 km and in Shimoga district its length is 32.2 km. Figure 1 depicts the location of the study area in India and Karnataka. Sharavathi river basin falls in two districts namely Uttara Kannada and Shimoga. Upstream river basin extends to two *taluks* in Shimoga viz. Hosanagara and Sagara. The entire basin has an area of 2985.66 km^2 with upstream and downstream respectively 1988.99 km^2 and 996.67 km^2 each. The basin slopes from west to east. The general elevation along the basin is about 640 m above sea level in the west. The western side of the upstream river basin rests upon the Western Ghats also known as the Sahyadri, which is a very mountainous area. The raise towards the crest of the Ghats is very rapid, a height of 1343 meters at Kodachadri according to the Survey of India. Figure 3 gives the digital elevation model of upstream. Slope percentage map derived from digital elevation model was classified into various slope groups.

Figure 4 classifies slope into 5 major slope groups. This classification is given in Table 1. Steep to strongly sloping are characteristics of *malnadu* (mountainous region) on the western side and is covered by dense vegetation such as evergreen/semi-evergreen and moist deciduous forests. Slopes attain nearly level ground at

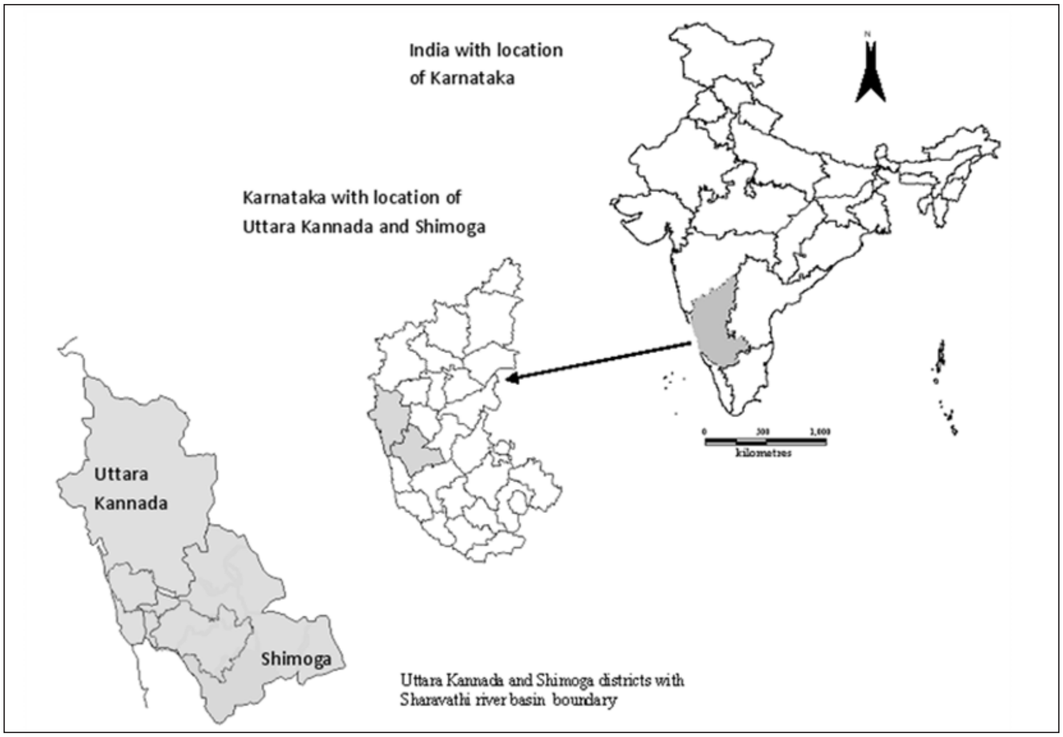

Fig. 1. Study Area – Sharavathi river basin, Karnataka state, India

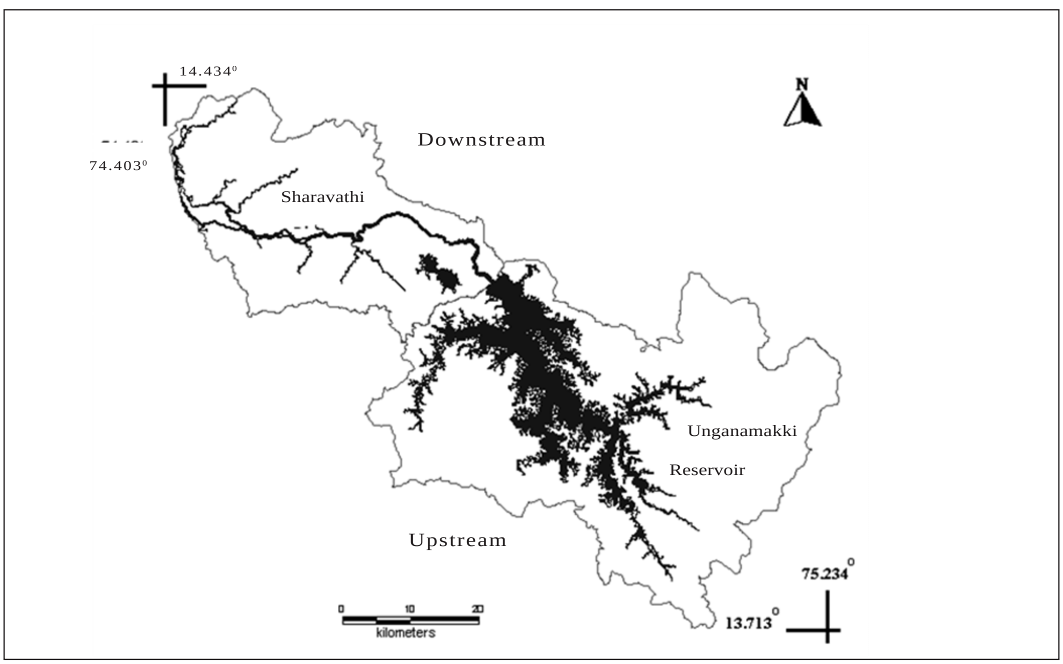

Fig. 2. Sharavathi River Basin –Upstream and Downstream

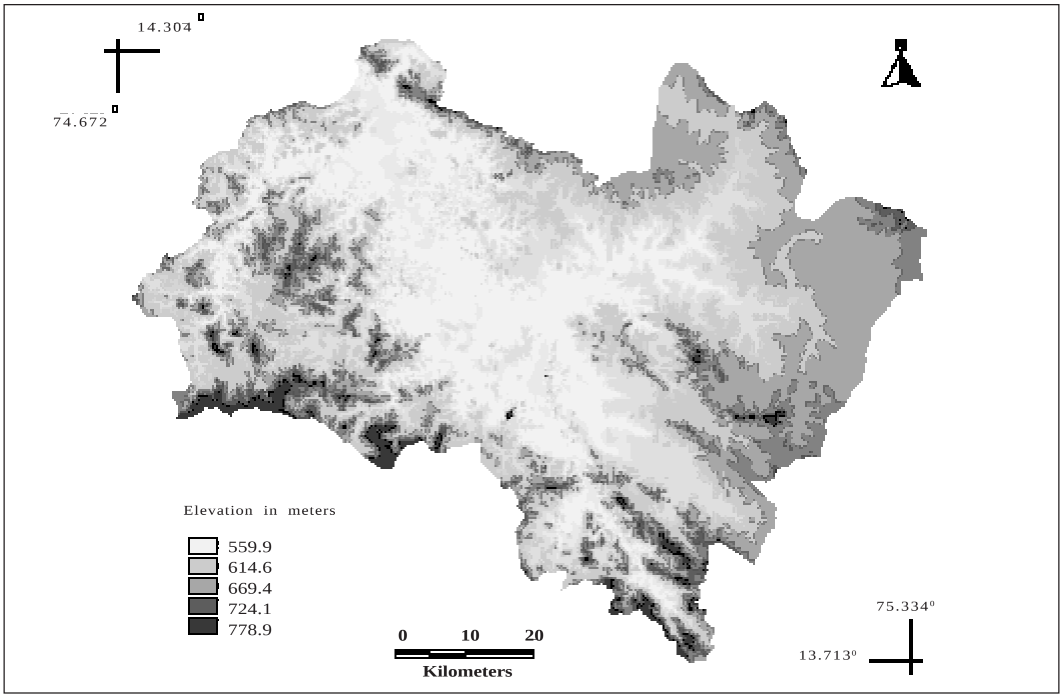

Fig. 3. Digital Elevation Model – Sharavathi upstream

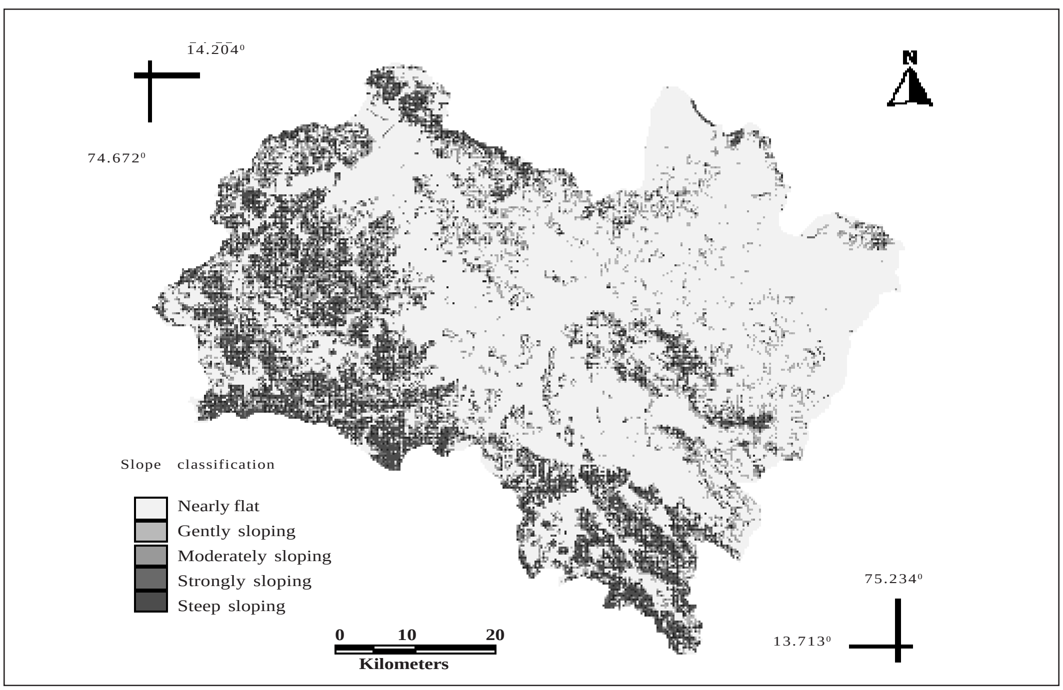

Fig. 4. Slope Classification – Sharavathi upstream

Table 1: Slope classifications

Slope in percentage	*Slope group*
0-10	Nearly flat
10-15	Gently sloping
15-20	Moderately sloping
20-30	Strongly sloping
30-80	Steep sloping

the centre of the basin (reservoir) and gently slope upward towards the east. Eastern portion especially Haridravathi and Nandiholé sub basins consists of nearly level or flat land, where paddy cultivation is practiced. As can be seen from Figure 5, dense drainage network is observed in the western portion of the basin. These are areas of very steep to steep slopes. Eastern portion especially, Nandiholé and Haridravathi basins with gentle slope are characterized by less dense network. In areas of high permeability soil (such as sand) *viz*. in Haridravathi and Nandiholé, the drainage density is low as compared with low permeability soil (clay) and high drainage density on the western side for example Yenneholé, Hurliholé etc. Sub-basins have been delineated according to the main tributaries flowing into the reservoir as depicted in Figure 6.

The climate in the study area is characterized by the monsoon regime, which superimposes itself over a regime of thermic convectional rainfall lined to the zenithal passage of the sun. The cold season is from December to February and is followed by the hot season which is from March to May. The rainfall is very heavy in the region of Western Ghats especially along the western side of the river basin. Mean annual rainfall ranges from 4500 mm in the western side to 1700 mm in the eastern side of the basin. About 95% of the rainfall is received during the south west monsoon months, June to September, July being rainiest. There is some rainfall in the post monsoon season, particularly in October, and it is mostly in the form of thundershowers. Some rainfall in the form of thundershowers also occurs during the summer months of April and May. After January, there is a rapid increase of tem-

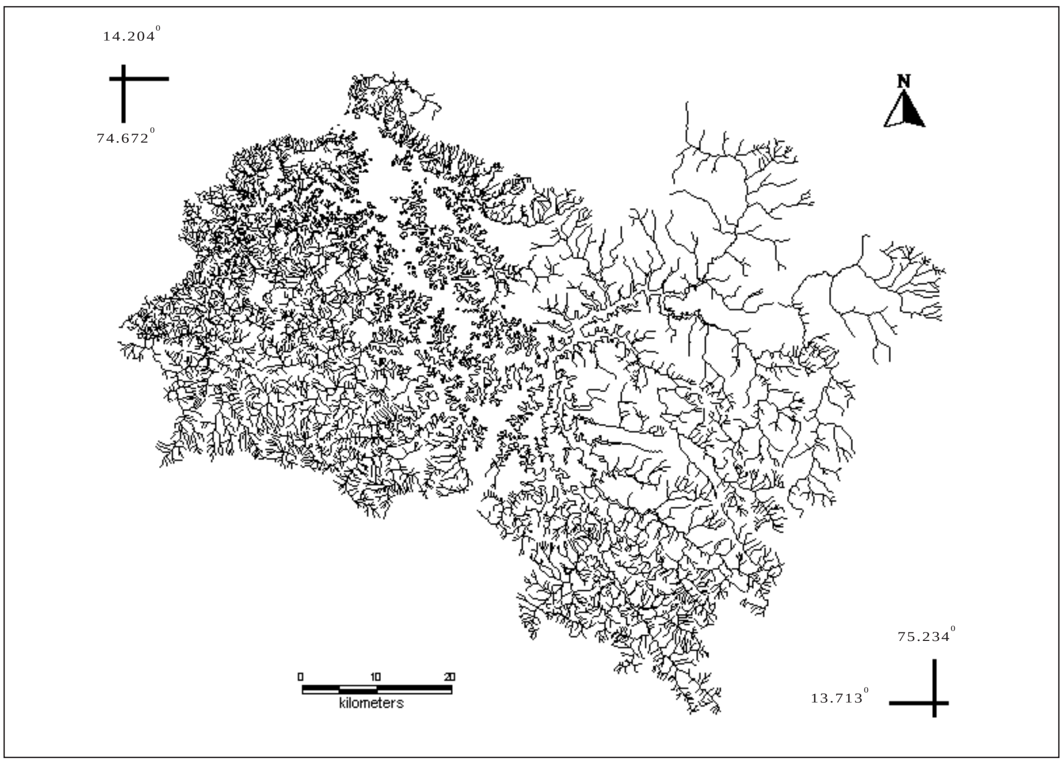

Fig. 5. Drainage – Sharavathi upstream

Fig. 6. Sub basins of Sharavathi upstream

peratures. April is usually the hottest month with the mean daily maximum temperature at 35.8°C and the mean daily minimum at 22.2°C. The relative humidity during the mornings throughout the year generally exceeds 75%. During the monsoon months, the relative humidity in the afternoon is quite high and is ~90 %. The driest part of the year is the period from January to March when the relative humidity is less than 35%.

Evergreen to semi-evergreen forests are confined to the western part of the basin. Many of the hills are covered with heavy forests while ravines and valleys produce luxuriant trees known for their great height and size (KSG 1975). Scattered shrubs and thickets are found in the regions surrounding the reservoir. Moist deciduous forests are found in the northern and eastern part of the study area. Plantations include acacia, teak, areca, rubber, eucalyptus etc. Areca nut also called betel nut is a widely used article of consumption and is grown in valleys. Acacia plantation is found in patches, amidst evergreen forests and is mainly used for paper production. Plantation constitutes 7-9% of the total vegetation in the upstream. Evergreen /semi-evergreen and moist deciduous forests constitutes 11% and 25% respectively.

DATA AND METHODS

Remote sensing and collateral data used for the analysis are:

Satellite Data

Table 2 gives information on the satellite data used in the study.

Table 2: Satellite/sensor details

Satellite/sensor	*Date of Pass*	*Path/Row*	*Bands*	*Source*
Landsat TM	Nov, 1989	146/50	2,3, 4,5,6 and 7	http:// glcf.umiacs.umd.edu
IRS LISS III	Mar, 1999	97/63	1,2,3 and 4	NRSA, Hyderabad

Note: Data for March 1989, was not available for IRS LISS III, while for 1989, only Landsat data was available.

Ground Truth and Ancillary Data

GPS points along with attribute information were collected in upstream to determine the type of land cover and land use such as vegetation, which includes evergreen-semi-evergreen and moist deciduous forests and plantations, degraded vegetation, agricultural activities, settlements, etc.

Maps and other ancillary data used for the study include:

i. Forest Map of South India (1982) by J.P. Pascal, French Institute of Pondicherry.
ii. Soil map published by the National Bureau of Soil Survey.
iii. Topographic maps of scale 1:50000 and 1:250000 from the Survey of India (SOI)
iv. Reconnaissance Soil Map of Forest Area, Western Karnataka and Goa
v. Geology map, Department of Mines and Geology
v Bio-climate of the Western Ghats (1982), J.P.Pascal, French Institute of Pondicherry.

Climate Data

i. IMD *Taluk*wise rainfall data (1901-2001) for Sagara, Hosanagara, Soraba and Tirthahalli (Shimoga) and Honnavara, Kumta and Siddapur (Uttara Kannada).
ii. Daily rainfall data from Karnataka Power Corporation Limited for 18 rain gauge stations in Sharavathi river basin (1989-1999).
iii. IMD maximum and minimum temperature data (1969-2000) for Shimoga.
iv. IMD extraterrestrial solar radiation and number of sunshine hours for Shimoga (1989-1999).
v. Water table level data (1989-1999) for selected wells in and around the study area from Dept. of Mines and Geology.

Remote Sensing Data Analysis

This involved the initial processing of remote sensing data to correct for geometric distortions, to calibrate the data radiometrically and to eliminate the noise present in the data. Creation of false colour composite (FCC) consisted of assigning primary colours to gray values from near infrared, red and green bands (Figs. 7 and 8). This helped in identifying heterogeneous patches, which were chosen for ground data collection (training polygons). Common classification procedures like supervised classification and unsupervised classification were adopted. Unsupervised classification involves clustering algorithms that examine the unknown pixels in an image and aggregate them into a number of classes based on the natural groupings or clusters present in the image values (Lillesand and Kiefer 2002). Supervised classification was done using Gaussian maximum likelihood classifier (GMLC) to classify the remote sensing data. GMLC uses the mean, variance and covariance data of the signatures to estimate a probability that a pixel belongs to each class. It tends to be more accurate if a large number of training sites are available. Here, the distribution of reflectance values in a training site is described by a probability density function, developed on the basis of Bayesian statistics.

Estimation of Hydrological Components

The aim here has primarily been to predict the amount of discharge from a basin apart from modelling water movement with in the basin through spatially distributed models. Attempts have been made in the development and application of hydrological models at a range of spatial levels, from plot to catchment, and temporal scales from event based models to annual water budgeting (Skidmore 2000). Figure 9 gives the flow chart of the method used in estimating each hydrological component. In order to capture the movement of water with in the basin, a spatially explicit approach using temporal remote sensing data is appropriate. It aids in quantifying land surface parameters that serves as input to the model in a spatially continuous fashion. Water budgeting of a basin describes the water movement with in the basin and the relation between the input, storage and output of water, which is given as:

Input –Output = Change in Storage in the system ……1

The following factors combine to express the water balance equation

Input: Direct precipitation (R) and Groundwater discharge (GD)

Output: Interception (I); Surface runoff (SR); Pipeflow (Pf: sub surface flow); Transpiration (ET: Evapo-transpiration from vegetation); Evaporation (E: evaporation from soil and open water); Groundwater recharge (GR). Equation 1, can be written as

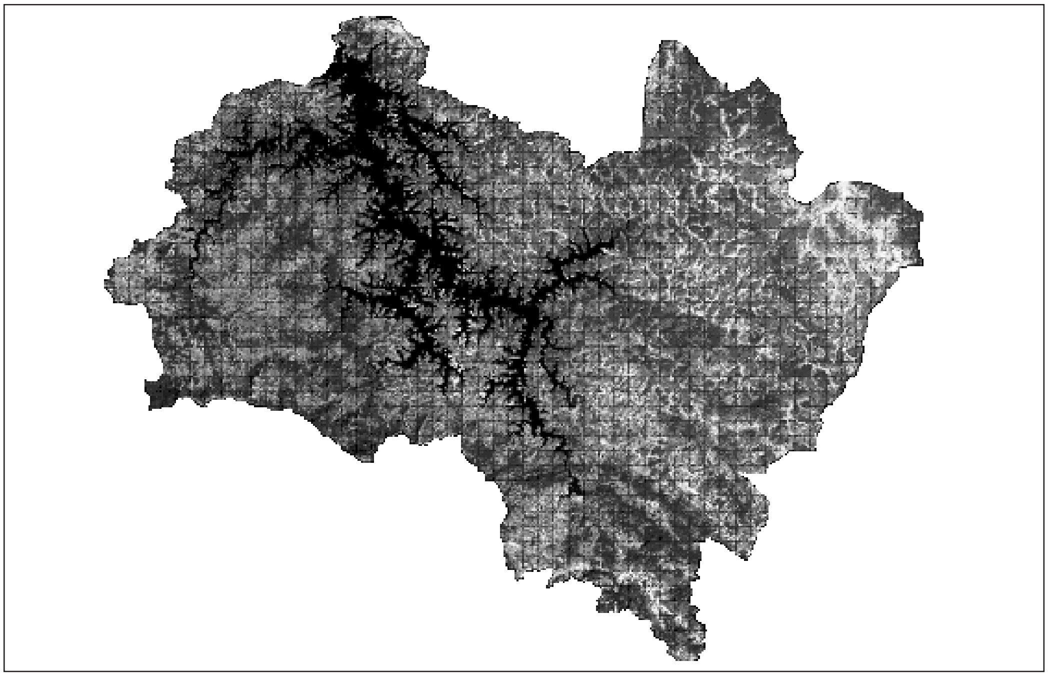

Fig. 7. Landsat TM, 1989 FCC

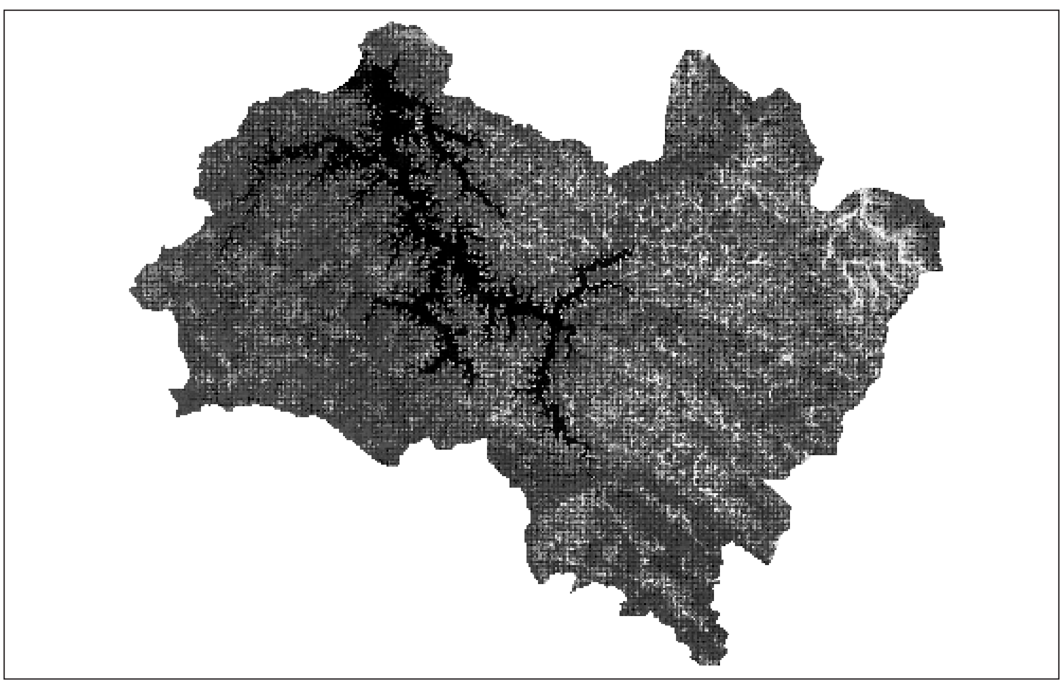

Fig. 8. IRS LISS III, 1999 FCC

Note: TM – Thematic Mapper
IRS – Indian Remote Sensing Satellite
LISS – Linear Imaging Self Scanning

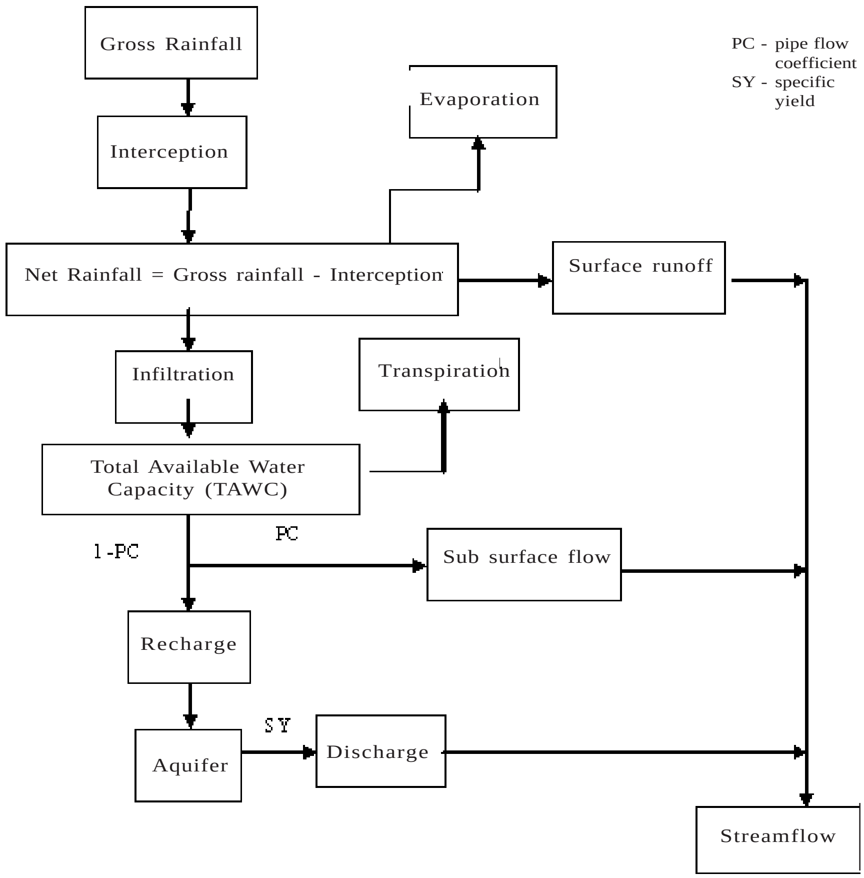

Fig. 9. Estimation of hydrological components

P ±GWD ±I ± SR ± Pf ±ET ±E±GR = ±DS ……… 2

Methods adopted for quantifying various hydrological constituents (Darcy 1856; Saint-Venant 1871; Singh 1992) are: P (Singh 1992; Raghunath 1985), I (Rutter et al. 1971; Calder and Newson 1979; Gash 1979; Singh 1992), SR (Horton 1933; Brakensiek 1967; Raghunath 1985), Pf (Putty and Prasad 2000), ET (Penman 1948; Turc 1961; Homes 1961; Monteith 1965; Shuttleworth and Calder 1979; Shuttleworth 1993), GR (Raghunath 1985; GWEM 1997), GD (Barnes 1939; Bruijnzeel 2004).

RESULTS AND DISCUSSION

Hydrological integrity of a river basin ensures the maximum amount of water available naturally as stream flow, soil moisture etc., to meet ecological and social (domestic, irrigation and livestock) demands in a river basin. Monthly monitoring of hydrological parameters reveal that stream in the catchments with good forest (evergreen to semi-evergreen and moist deciduous forests) cover have reduced runoff as compared to catchments with poor forest covers. Runoff and thus erosion from plantation forests was higher from that of natural forests. Forested catchment have higher rates of infiltration as soil are more permeable due to enhanced microbial activities with higher amounts of organic matter in the forest floor (Ramachandra et al. 2013a). Streams with good native forest cover in the catchment showed good amount of dry season flow for all 12 months. While strems in the catchment dominated by agricultural and monoculture plantations (of Eucalyptus sp. and *Acacia* *auriculiformis*) are sesonal with water availability ranging between 4-6 months. This highlights the impacts of land use changes in tropical forests on dry season flows as the infiltration properties of the forest are critical on the available water partitioned between runoff and recharge (leading to increased dry season flows). This emphises the need for integrated watershed conservation approaches to ensure the sustained water yield in the streams.

Land Use Change

Sharavathi river basin in the Western Ghats has been a subject of research and debates due to its ecologically rich environment (Ramachandra et al. 2013b; Ramachandra et al. 2014b). The 1940 SOI toposheet show that the entire river basin was covered with forests. Table 3 gives the percentage change analysis of forest cover (reserved forests) based on 1940 toposheets (48K/13, 48J/16 and 48O/1), and 1989 (Landsat TM) and 1999 (LISS III) imageries. This shows that more than 50% of the forests have decreased/removed by human activities and submergence due to damming the Sharavathi River.

Classified remote sensing data corresponding to the upstream of Sharavathi river basin (upstream) for 1989 and 1999 are given in Figures 10 and 11 respectively. Table 4 gives the error matrix generated for Landsat TM 1989 classified data, which indicates an overall accuracy of classification as 96.4%. Similarly, Table 5 lists the confusion matrix (error matrix) for IRS LISS III data with an accuracy of 97.6%. Low accuracy for settlements from both the imageries is

Table 3: Changes in Reserve Forests Area (1940-1999)

1940 (sq.km)	*1989 (sq.km)*	*1999 (sq.km)*	*Change in % (1940-1999)*
185.09	99.46	89.73	-51.52%

Table 4: Error matrix (Landsat TM 1989)

	Evg/SE	*MD*	*Plant*	*Grass*	*Agri*	*Open*	*Sett*	*Water*	*Total*
Evg/SE	4125	0	0	0	0	0	0	0	4125
MD	208	319	2	0	0	0	0	0	529
Plant	2	1	85	0	0	0	0	0	88
Grass	0	0	0	17	0	0	0	0	17
Agri	0	0	0	0	326	0	0	0	326
Open	0	0	0	1	1	62	0	0	64
Sett	0	0	0	0	0	9	8	0	17
Water	0	0	0	0	0	0	0	1211	1211
Total	4333	320	87	18	327	71	8	1211	6377

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements

Table 5: Error matrix (IRS LISS III 1999)

	Evg/SE	*MD*	*Plant*	*Grass*	*Agri*	*Open*	*Sett*	*Water*	*Total*
Evg/SE	553	0	19	0	0	0	0	0	572
MD	0	586	0	0	0	1	0	0	587
Plant	17	0	101	0	0	0	0	0	118
Grass	0	0	0	191	0	0	0	0	191
Agri	0	0	0	1	168	0	0	0	169
Open	0	0	0	0	0	278	0	48	326
Sett	0	14	0	0	0	0	7	0	21
Water	0	0	0	0	0	0	0	981	981
Total	570	600	120	192	168	279	7	981	2965

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements

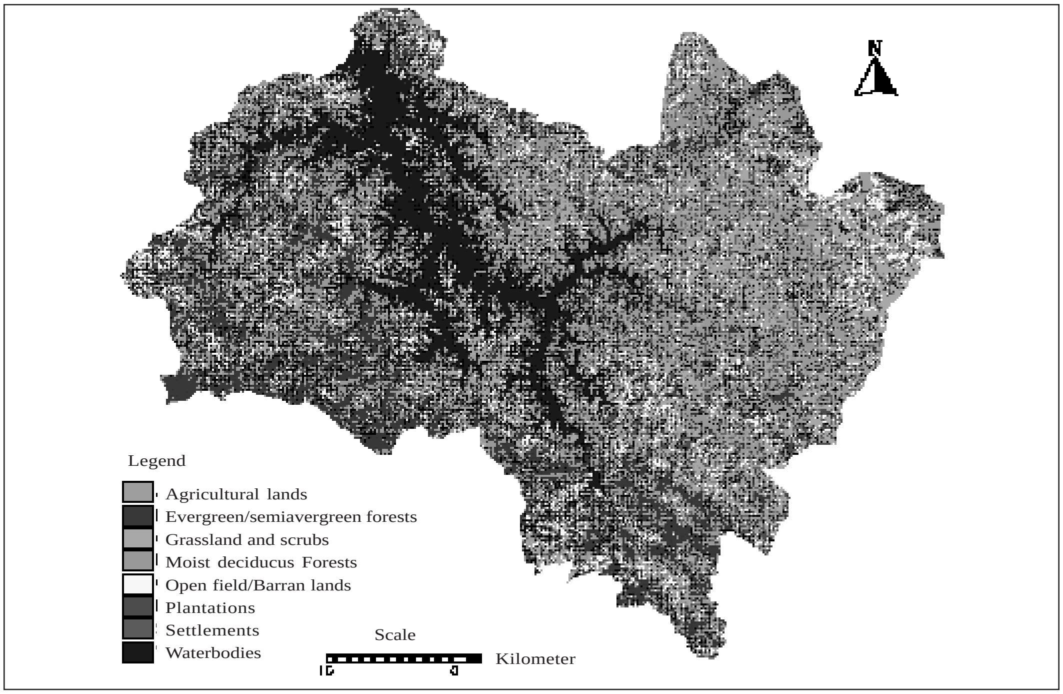

Fig. 10. Land use classification (Landsat TM 1989)

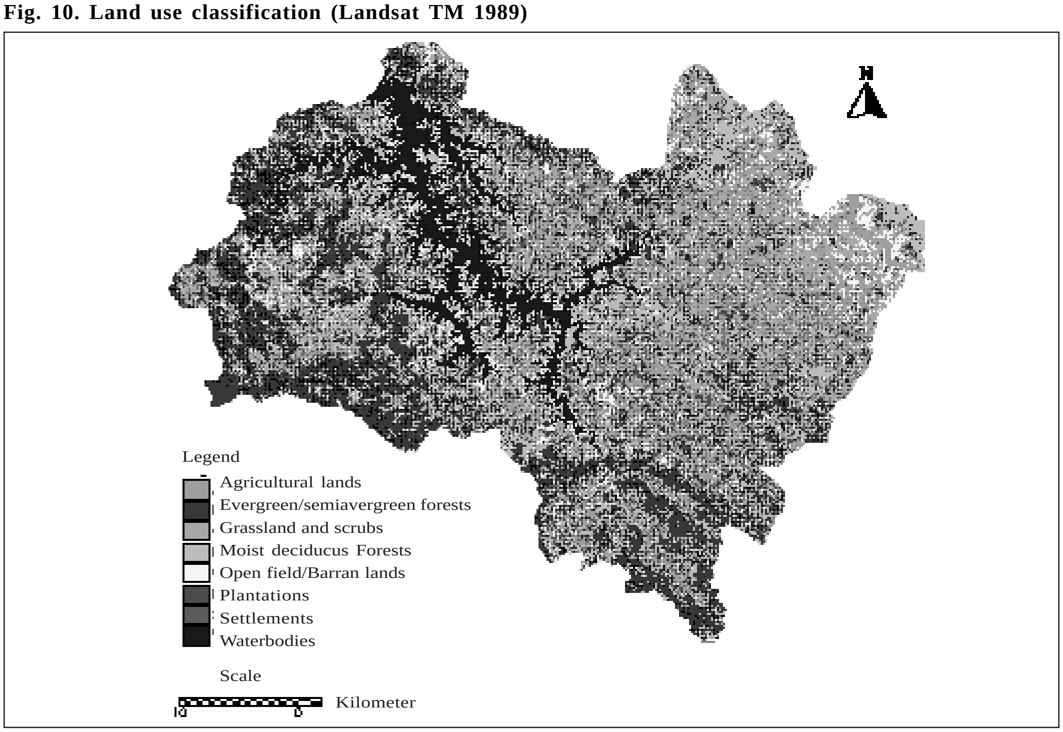

Fig. 11. Land use classification (IRS LISS III 1999)

partly due to spectral signature overlap with vegetation as most of the houses are surrounded by vegetation inside and outside the compound. Townships are few and houses are sparsely distributed separated by hundreds of meters. Since the building material is also different as almost all houses have tiled roof than concrete, overlap also occurred between open fields. Overlap of spectral signatures was also observed between evergreen/semi-evergreen forest and moist deciduous forests in full leaf.

Table 6 compares the percentage change in the land use in Sharavathi upstream river basin based on 1989 and 1999 data. It is seen that natural forests such as evergreen/semi-evergreen and moist deciduous forests have decreased by 28.2% whereas monoculture plantations (due to afforestation work of the forest department) have increased by 17.3%. Grasslands and scrubs have decreased by 28.4% in 1999 but this can be attributed to the season as in summer, grasses dry out leaving only the scrubs. The main anthropogenic activity apart from plantation is paddy cultivation, which has increased by 5% in 1999. Paddy cultivation is the most common agricultural activity in the basin and is usually grown in valleys.

Human population is increased in the basin and there has been immigration of people from adjoining districts of Karnataka and also from neighbouring States. Although the dam has provided electricity, water and other benefits to the surrounding areas, it has proved to be at the cost of the valuable ecosystem. Evergreen forests are being cleared to yield timber, which are used for electric transmission poles and railway sleepers. The felled areas are sometimes tended for getting the natural regeneration of valuable species. Deciduous forests supply timber, firewood, charcoal, bamboo, matchwood and plywood. Monoculture plantations of teak, silver oak *(Gravillea robusta)*, matchwood, Acacia sp., etc. are planted by the forest department in clear felled forest areas. Table 7 give the sub-basin wise area under different land uses.

Rainfall Analysis

Yearly data for hundred years were available for 7 *taluks* in and around the river basin *viz*. Hosanagara, Sagara, Soraba and Tirthahalli (Shimoga district) and Honnavar, Kumta and Siddapur (Uttara Kannada district). Since these are the *taluks* surrounding the river basin, rainfall analysis is done to study any variation in rainfall for 100 years. The rainfall periods were divided into 1901-1964 and 1964-2001, which represents respectively the periods before construc-

Table 6: Changes in land use in upstream (1989-1999)

Land use/Land cover	*1989 (km^2)*	*1999 (km^2)*	*Change in %*
Evergreen/semievergreen forests	272.67	209.39	- 23.2
Moist deciduous forests	539.26	512.25	- 5
Plantations	122.09	143.29	+17.3
Grasslands and scrubs	433.98	310.6	- 28.4
Agricultural lands	102.77	157.36	+ 53.1
Open fields/Barren lands	247.96	430.29	+ 73.5
Settlements	52.63	78.48	+ 49.1
Water bodies	218.01	147.31	-32.4

Table 7: Land use in the upstream of Sharavati (Sub basinwise in sq.km)

Sub basins	*Evg/SE*	*MD*	*Plant*	*Grass*	*Agri*	*Open*	*Sett*
Yenneholé	54.22	45.52	29.27	22.82	2.07	38.5	6.05
Nagodiholé	26.17	15.21	8.87	3.09	.03	8.42	2.81
Hurliholé	22.14	30.45	7.99	13.37	1.24	18.26	3.08
Linganamakki	50.47	202.38	55.41	13.37	50.47	194.91	25.72
Hilkunji	25.79	30.02	5.57	6.53	4.94	9.9	3.67
Sharavathi	16.29	40.66	14.16	16.35	19.37	27.31	7.06
Mavinaholé	2.36	33.9	4.87	20.47	10.3	18.08	6.62
Haridravathi	3.87	64.87	11.65	79.9	49.93	73.39	14.34
Nandiholé	2.22	48.48	5.19	52.71	18.71	41.03	8.96

Note: Evg/SE - evergreen/semievergreen forests; MD – moist deciduous forests; Plant – plantations; Grass – grasslands and scrubs; Agri – agricultural lands; Open – open fields; Sett- settlements tion and after construction of Linganamakki dam. Table 8 gives the mean and standard deviation of rainfall in Shimoga district. Hosanagara, Sagara, Tirthahalli and Siddapur *taluks* showed reduction in the mean annual rainfall with a significant reduction in Tirthahalli *taluk*. Sagara and Hosanagara were selected for further studies as these districts cover the study area.

The sub-basins were further classified into clusters viz. west, east, south and central depending on their geographical locations. Rainfall data were available for 18 rain gauge stations (within the upstream) from 1989-1999. The mean rainfall (1989-1999) was determined for each sub basin in order to observe the rainfall variation and distribution within the river basin. They were classified as follows:

- West-Yenneholé, Nagodiholé and Hurliholé
- Central-Linganamakki
- East- Nandiholé, Haridravathi and Mavinaholé
- South- Sharavathi and Hilkunji

Figure 12 illustrates the mean annual precipitation variability in western and eastern sub-basins.

Regression analysis was carried out for each rain gauge station considering rainfall as dependent variable and latitude, longitude, altitude and land cover as independent variables. The area of influence of each rain gauge station in the upstream was delineated with respect to contours and drainage and the land cover expressed as NDVI was determined using the imagery for each area around the gauge. Regression analysis showed rainfall having significant relationship with variables such as land cover, latitude, longitude, and altitude. At 5% level of significance rainfall showed good relationship between land cover, latitude, altitude and longitude. The probable relationships are given in Table 9. From the regression relationship, it is evident that the rainfall increases with land cover (NDVI) and decrease with latitude, longitude and altitude. Sensitivity analysis show the relationship holds good for all sub basins in the upstream region of the river basin.

Table 8: Variation of rainfall in Shimoga

Taluk	*1901-2001 (mm)*	*COV (%)*	*1901-1964 (mm)*	*COV (%)*	*1965-2001 (mm)*	*COV (%)*	*Change in rainfall (%)*
Hosanagara	2813.9 ± 754.4	26.8	2854.2 ± 683.4	23.9	2752.8 ± 859.9	31.2	-3.55
Sagara	2098.1 ± 523.6	24.9	2144.5 ± 560.3	26.1	2018.4 ± 444.2	22	-5
Soraba	1583.8 ± 430.0	27.1	1627.3 ± 388.6	23.8	1511.4 ± 488.6	32.3	2.4
Tirthahalli	3051.8 ± 783.6	25.6	*3132.9 ± 841.4	26.8	2742.6 ± 607.0	22.1	-12.45
Honnavar	3485.1 ± 687.8	19.7	3360.6 ± 775.4	23	3636.3 ± 565.5	15.55	8.2
Kumta	3755.9 ± 750.7	19.9	3633.8 ± 831.9	22.8	3391.1 ± 575.3	16.9	-6
Siddapur	2999.8 ± 769.9	25.6	3037 ± 793.2	26.1	2935.6 ± 734.4	25	-3.3

Table 9: Probable relationships of rainfall

X (independent)	*Y (dependent)*	*Probable relationships*	*r*	*p*
Latitude	Rainfall	Rainfall = -6541.28 (latitude) +95120.76	0.45	0.043
Land cover	Rainfall	Rainfall = 1243.97 (land cover)-3679.31	0.71	0.0
Longitude, latitude	Rainfall	Rainfall =(1864.41(long) -8504.99(lat)+262543.8	0.56	0.036
Longitude, land cover	Rainfall Rainfall	Rainfall = -234.71 (long) +1232.78 (land cover)+	0.71	0.002
Altitude, land cover	Rainfall	Rainfall = -4.33 (alt)+1273.63 (land)-1201.39	0.72	0.002
Land cover, latitude	Rainfall	Rainfall = -4.33 (alt)+1273.63 (land)-1201.39	0.74	0.001
Longitude, altitude, latitude	Rainfall	Rainfall = - 1868.78 (long)-8989.5 (lat) -4.97 (alt)+ 272688.8	0.58	0.076
Longitude, latitude, land cover	Rainfall	Rainfall = -926.48 (long) -4486.52 (lat) +997.16 (land)+130029.1	0.75	0.003
Altitude, land cover, longitude	Rainfall	Rainfall = - 4.2 (alt) +1264.58 (land) -171.13 (long)+11623.16	0.72	0.007
Land cover, altitude, latitude, longitude	Rainfall	Rainfall = 1016.06 (land) -6.07 (alt) -5002.23 (lat) -914.05 (long)+139910.8	0.77	0.005

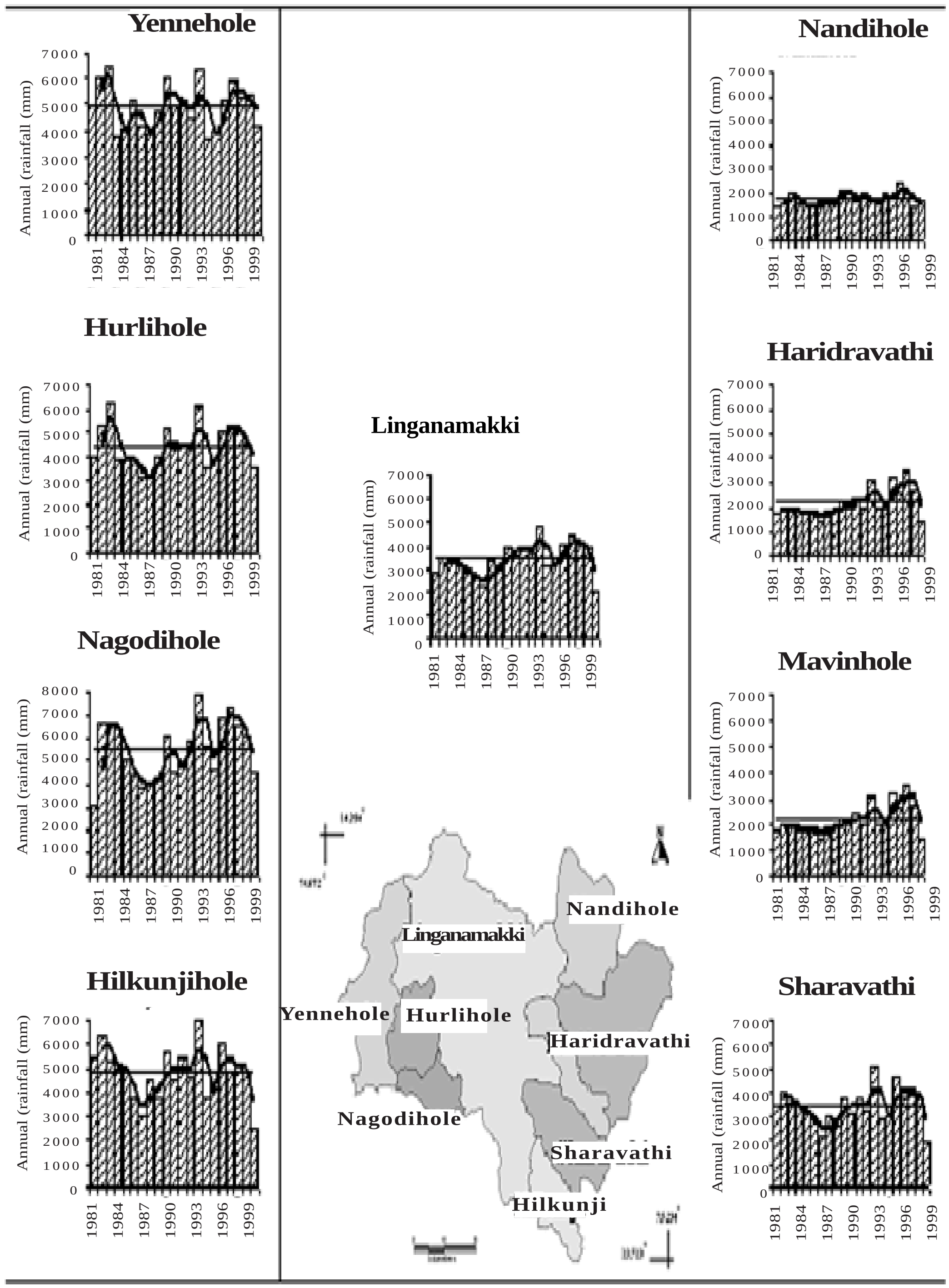

Fig. 12. Annual rainfall pattern in last two decades in the sub-basins of Sharavathi river upper catchment

Interception

Evergreen forests are multilayered and are replete with climbers: lianas and epiphytes. They also have a thick canopy, which can attribute to higher interception in evergreen forests. It is followed by moist deciduous forest which even though have large leaves are more open compared to evergreen/semi-evergreen forests. The structure and composition is also different. There is no layering but the amount of underbrush is high as compared to evergreen forests due to better light penetration. Evergreen/semi-evergreen forests are almost bare of ground vegetation and plants grow only if sufficient light penetrates through gaps in the canopies (Putty and Prasad 2000; Ramachandra et al. 2015). Plantations (acacia) show low values due to the smaller leaf size, which reduces the overall canopy interception. Acacia and areca constitutes a major portion of the plantation trees and have long narrow, vertically aligned leaves. Vertically aligned leaves intercepts lesser rainfall as compared to broad leaves. Areca plantations do have some understorey – small shrubs that yields fruit and sometimes mulching with green leaves is practiced to prevent soil erosion during high intensity precipitation. Paddy intercepts the least rainfall, which shows that interception is highest in trees than in crops or grasses (Calder and Newson 1979; Gash et al. 1980; Lloyd et al. 1988; Shuttleworth 1989; Singh 1992). Interception is highest during July as it receives the highest rainfall and lowest during September and October as these months receive the lowest rainfall in the basin (Fig. 13). Table 10 clearly shows the increase in interception with vegetation and rainfall. High interception in western sub basins is due to good vegetation cover such as evergreen/semi-evergreen forest and moist deciduous forests whereas the vegetation cover such as natural forests is lesser in eastern sub basins. Plantations and agricultural activities are higher in the eastern and southern basins.

Table 10: Percentage of interception w.r.t rainfall

Sub-basins	*Interception (%)*
Yenneholé	26.13
Nagodiholé	28.21
Hurliholé	26.73
Linganamakki	24.92
Hilkunji	27.69
Sharavathi	25.48
Mavinaholé	23.61
Haridravathi	21.82
Nandiholé	23.29

Runoff

The most common drainage pattern found in upstream river basin is dendritic. However, the drainage density differs from west to east of the

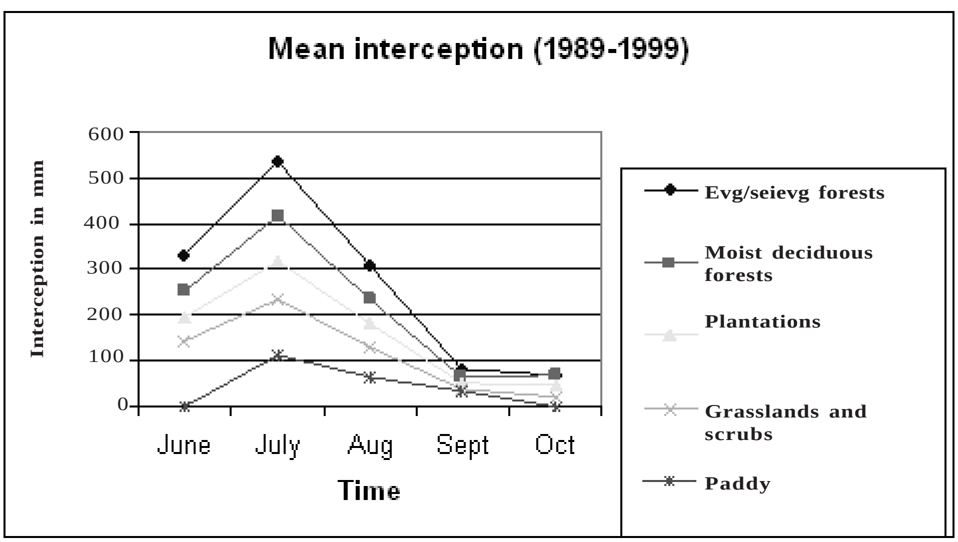

Fig. 13. Mean Interception for Different Vegetation Types

basin that is it decreases from west to east. High drainage densities usually reduce the discharge in any single stream, more evenly distributing runoff and speeding runoff into secondary and tertiary streams. Where drainage density is very low, intense rainfall events are more likely to result in high discharge to a few streams and therefore a greater likelihood of "flashy" discharge and flooding in humid areas and suggests resistant bedrock. Table 11 lists the drainage densities and sediment yields in the sub basins.

Western sub-basins, which are highly vegetated show the highest values due to steep slopes and clayey soil texture. Sediment yield is inversely proportional to vegetation cover. Though western sub basins have steeper slopes compared to eastern sub basins for example Nandiholé, good vegetation cover in the former impedes much of the sediment load and thus erosion during high rainfall events. Table 12 gives the mean monthly surface runoff from each sub basin. Surface runoff progressively increases from evergreen/semi-evergreen forests to settlements, indicating that where there is good vegetation cover, surface runoff is less. Forests usually have thick leaf litter and a spongy humic horizon, both of which retard surface runoff or overland flow. Among the forest types, plantation forests showed higher runoff. Certain species such as *Tectona Grandis*, which are mostly found in the eastern sub basins, cause severe erosion. This is due to the large leaves, which produce big raindrops, which roll of the leaves, and causes splash and subsequently rill erosion if not protected by underbrush.

Table 11: Drainage density and sediment yield

Sub-basins	*Drainage density (km/km^2)*	*Sediment yield (x 10^6 m^3/year)*
Yenneholé	2.43	0.016
Nagodiholé	2.8	0.040
Hurliholé	2.6	0.019
Linganamakki	0.9	0.354
Hilkunji	2.16	0.057
Sharavathi	1.64	0.087
Mavinaholé	1.42	0.057
Haridravathi	1.01	0.176
Nandiholé	0.74	0.11

Groundwater Recharge and Discharge

Groundwater recharge analysis results are given in Table 13. The rate of replenishment or recharge is dependent on the soil moisture status, which in turn is dependent on soil texture. Soil texture in the study area varies from loamy sand to clay loam. From soil studies (Kumar and Ramachandra, 2005), sand is an important constituent in the basin and is responsible for high infiltration rates. Average recharge in the basin is 30.3% of the rainfall. Total mean monthly recharge is observed to vary from west to east with the eastern sub basins receiving the least recharge. Mean monthly recharge under different land use indicate that recharge under vegetation is higher as compared to other land cover types.

The determination of groundwater volumes and flow rates requires a thorough knowledge of the geology of the groundwater basin (Viessman 1989). The geologic structure of a groundwater basin governs the occurrence and movement of the groundwater beneath it. Base flow contribution to stream flow varies widely according to the geologic nature of the aquifer. The two major rock types occurring in the basin are gneisses /granites and greywackes. Gneisses and granites have the lowest specific yield (3%) and occur in the eastern portion of the study area such as Mavinahole, Haridravati and Nandi-

Table 12: Mean monthly surface runoff (1989-1999)

Months Sub-basins	*June (mm)*	*July (mm)*	*August (mm)*	*September (mm)*	*October (mm)*	*Total (mm)*
Yenneholé	311.05	499.64	309.65	79.89	48.06	1241.96
Nagodiholé	398.42	603.27	343.27	86.37	96.16	1496.39
Hurliholé	305.97	499.79	256.57	69.39	54.67	1180.72
Linganamakki	324.11	530.22	290.1	71.36	81.74	1287.72
Hilkunji	257.06	408.14	232.17	59.98	47.94	1000.1
Sharavathi	262	364.06	176.1	48.39	76.35	914.29
Mavinaholé	218.79	356.71	176.64	52.68	80.48	871.5
Haridravathi	262	364.06	176.1	48.39	76.35	702.28
Nandiholé	141.28	217.82	139.67	42.08	95.44	623.9
Upstream	266.42	421.37	236.88	62.71	82.12	1058.05

Table 13: Mean monthly recharge (1989-1999)

Months Sub-basins	*June (mm)*	*July (mm)*	*August (mm)*	*September (mm)*	*October (mm)*	*Total (mm)*
Yennehole	373.61	620.46	380.94	98.59	46.94	1513.76
Nagodihole	506.22	770.94	438.34	109.72	65.5	1883.3
Hurlihole	329.02	546.28	280.09	75.23	58.44	1282.99
Linganamakki	280.83	495.75	270.88	66.03	58.7	1164.7
Hilkunji	294.71	503.31	286.14	73.55	45.44	1198.12
Sharavathi	212.25	338.87	163.59	44.53	52.81	803.28
Mavinahole	178.7	291.96	144.72	42.68	65.12	712.04
Haridravati	125.9	217.48	135.84	42.98	63.57	576.13
Nandihole	119.75	205.33	131.17	39.17	56.17	544.55
Upstream	220.16	360.62	200.06	55.44	59.33	886.71

hole. Hence, streams here are ephemeral indicating baseflow only during monsoon season. Western sub basins have perennial streams, which is an indication of the rock types present in the area. The region consists of greywackes, which has higher specific yield of 27%. Another important reason for better discharge in western sub basins is the good vegetation cover. Natural forests retard much of the overland flow facilitating in enhanced infiltration and thus recharge. In other words, regardless of the geology the amount of water entering an aquifer is dependent first on the vegetation and soil present in the area. Forestlands cleared for agriculture or other purposes increases overland flow thus decreasing recharge and subsequent discharge into the streams.

Mean monthly water table levels in the select observation wells showed similar seasonal fluctuations that is water table rises during monsoon season and thereafter decreases. Water table is almost steady during August to September and decreases with the maximum decline in the month of May. Decrease in water levels is partly due to natural discharge or base flow and partly due to artificial extraction of groundwater. Streams located south of the basin receive substantial base flow during non-monsoon season. The amount of base flow decreases from south to east such as Nandihole and Haridravati. It is observed that wells in the region have reported decrease in water levels and as such fail to provide base flow during the lean season. Streams in these sub basins are ephemeral. The total change in storage for each sub basin is given in Table 14. Storage consists of the water contained in soil and the underlying rock. Higher storage in western sub basins is responsible for the lush vegetation present in these areas. Mean annual volumes of hydrological components in each sub basin are given in Table 15.

Table 14: Total storage in Sub-basins

Sub-basins	*Mean Total Storage (x 10^6 M cu.m) (June-Oct)*
Yenneholé	233.09
Nagodiholé	171.56
Hurliholé	86.80
Linganamakki	834.69
Hilkunji	68.55
Sharavathi	70.54
Mavinaholé	48.03
Haridravathi	51.21
Nandiholé	17.6

The evergreen forests have high humidity thereby are the major driving forces in determining the amount of rainfall in these regions. Thus in the upstream, heavy rainfall occurs along Nagodi, Kogar and Aralagodu rain-gauge stations. Forest cover in these regions is also high (land cover analysis, land use analysis) indicating the close relationships between rainfall in Western Ghats regions with the type (evergreen, semi-evergreen, etc.) and spatial extent of vegetation cover (Table 16). Within the catchment area of Linganamakki, the areas surrounded by rich vegetation like Nagara, Karimane, Byakodu etc. receive high rainfall compared to fragmented, poorly vegetated eastern regions like Ulluru, Anandapura and Ripponpet.

It is found that western side sub-basins (Nagodiholé, Huruliholé, Yenneholé) have rain fall ranges from 4500-6500 mm and their stream flow is quite high having grade of A (perennial streams). Sub-basinwise stream flow is given in Table 17. South east region (Sharavathi, Hilkunji) has rain fall of around 5000mm with stream flow moderate to high having grading of B-C (stream

Table 15: Mean annual volumes of hydrological component (x 10^6 m^3)

Sub-basins	*R*	*I*	*ET*	*E*	*SR*	*Pf*	*GR*	*GD*
Yenneholé	983.6	191.96	80.7	25.37	281.78	0.67	286.79	26.47
Nagodiholé	374.68	86.63	32.22	6.7	88.91	0.79	115.75	16.98
Hurliholé	413.69	85.32	42.13	12.74	111.88	0.62	200.72	11.55
Linganamakki	2915.53	379.06	265.12	228.73	815.2	-	749.01	78.05
Hilkunji	337.85	77.31	39.45	7.72	83.03	0.8	99.38	9.23
Sharavathi	358.68	61.53	50.4	17.89	119.0	0.26	105.46	9.46
Mavinaholé	254.41	42.71	33.16	13.58	78.81	0.3	64.97	1.17
Haridravathi	555.82	77.56	90.3	51.25	188.13	-	184.79	3.25
Nandiholé	31.08	49.84	61.24	29.67	125.3	-	97.37	1.86

Table 16: Land-use pattern (%) and associated annual rainfall in the sub-basins of Sharavathi River upstream.

Locality	*Annual forests rainfall (mm)*	*EVG/SE*	*MD*	*Planta-tion*	*Grass-land*	*Agri*	*Open*	*Sett*
Nandiholé	1715.2	1.25	27.34	2.93	29.73	10.55	23.14	5.05
Haridravathi	1776.49	1.30	21.77	3.91	26.82	16.76	24.63	4.81
Mavinaholé	2157.88	2.44	35.09	5.04	21.19	10.66	18.72	6.85
Sharavathi	3382.4	11.54	28.80	10.03	11.58	13.72	19.34	5.00
Hilkunji	4801.25	29.84	34.74	6.45	7.56	5.72	11.46	4.25
Huruliholé	4410.05	22.94	31.54	8.28	13.85	1.28	18.92	3.19
Nagodi	5597.5	40.51	23.54	13.73	4.78	0.05	13.03	4.35
Yenneholé	4933.01	27.32	22.94	14.75	11.50	1.04	19.40	3.05
Linganamakki	3423.25	8.51	34.14	9.35	2.26	8.51	32.88	4.34

* Water body constitutes 15.8% of the region
Note: EVG/SE: Evergreen/semi evergreen; MD: Moist deciduous; Agri: Agriculture; open: open area; sett: settlements

flow for 6 – 9 months). Finally sub-basins of eastern side (Nandiholé, Haridravathi and Mavinaholé) have rain fall of 1400-3000 mm which is very less and their stream flow is also quite low, graded C-D (4 – 6 months: mostly during monsoon).

Natural and artificial forces operating over a watershed or a basin ultimately impacts its stream flow regime. Western clusters enjoy the benefit of good rainfall, vegetation and geology to give rise to stream flow even during the lean season. A contrast is seen on the eastern side as volume of stream progressively decreases from Hilkunji to Nandiholé sub-basins. Modification of land by agriculture and other uses, unfavourable geology, clearcutting of natural forests and poor rainfall have resulted in decline in base flow during the non-monsoon months and significant decrease during summer (Mar-May). The

Table 17: Stream flow data for major tributaries of streams in the Linganamakki catchment

Stream	*Location*	*Stream flow measurement (Discharge m^3/sec)*				*Stream Grading**
		Oct.	*Nov.*	*Dec.*	*Jan*	
Nandiholé	Northeast	01.23	03.68	0.09	0	D
Haridravathi	East	16.23	03.02	0.46	0	D
Mavinaholé	East	05.93	03.00	0.44	0	D
Sharavathi	Southeast	26.73	5.83	1.08	0.964	C
Hilkunji	Southeast	46.27	10.64	2.64	1.67	B
Nagodiholé	West	22.56	4.84	1.90	1.42	A
Hurliholé	West	06.30	1.37	0.78	0.661	A
Yenneholé	West	NM	13.40	1.81	1.68	A

* Based on numbers of months with flow a: 12 months, B: 9 months; C: 6 months and D: 4 months

study shows that spatial and temporal variation in rainfall corresponding to land use changes has significant role in the water yield in the catchment and hence the reservoir yield. Higher rainfall and the presence of perennial streams (and higher drainage density) in the Western side compared to the eastern side (relatively lower rainfall, poor drainage density and seasonal streams) is due to the large scale land use changes in the east.

CONCLUSION

This study explored and quantified the altered hydrological parameters due to large scale land use and land cover changes in a river basin. In this regard, remote sensing data has offered excellent inputs to monitor dynamic changes through repetitive, synoptic and accurate information of the changes. It also provided a means of observing hydrological state variables over large areas, which was useful in parameter estimation of hydrologic components. GIS offered means for merging various spatial themes (data layers) that was useful in interpretation, analysis and change detection of spatial structures and objects. Studies reveal the linkages among variables such as land use, hydrology and ecology:

i) Rainfall analysis based on one hundred years data for Sagara and Hosanagara show reduction of 3.55% and 5% respectively in the Sharavathi upstream river basin Regression analysis was carried out for each rain gauge station considering rainfall as dependent variable and latitude, longitude, altitude and land cover as independent variables. Regression analysis showed rainfall having significant relationship (5% level of significance) between land cover, latitude, longitude, and altitude. Sensitivity analysis show the relationship holds good for all sub basins in the upstream region of the river basin.

ii) Catchments with good forest (evergreen to semi-evergreen and moist deciduous forests) cover showed reduced runoff as compared to catchments with poor forest covers. Runoff and thus erosion from plantation forests was higher from that of natural forests. Erosion rates in undisturbed natural forest could be considered to represent a natural baseline or background erosion rates against which the erosion rates from all other land uses.

iii) Sub basins with good forest cover showed good amount of dry season flow for all 12 months with the flow decreasing as we move towards east. Decrease of low flows in eastern sub basins can be partly attributed to eucalyptus plantations. Eucalyptus trees have deep roots that tap water deep in the soil mantle creating severe soil moisture deficits. It may take many years of rainfall before field capacity conditions can be established and recharge of the groundwater aquifer and perennial flows can take place. Another reason is the low specific yield of the underlying rock.

iv) This highlights the impacts of land use changes in tropical forests on dry season flows as the infiltration properties of the forest are critical on the available water partitioned between runoff and recharge (leading to increased dry season flows).

v) The anthropogenic influences on the land cover are related to the land use for agriculture, plantation forestry and urbanisation. It was obvious from the present study that land use has an implication on the hydrological components operating in the river basin.

ACKNOWLEDGEMENTS

We are grateful to the Ministry of Science and Technology (DST), the Ministry of Environment and Forests, Government of India and Indian Institute of Science for the sustained financial support and infrastructure support. We thank Mr. Vishnu Mukri, Mr. Lakshminarayana for their assistance in the fieldwork, Ms. Saira for data analysis and Mr.Susamto Sen for proof reading the manuscript.

REFERENCES

Barnes BS 1939. The structure of discharge recession curves. *Trans Amer Geophysical Union*, 20: 721-725.

Bhat S, Kirk Hatfield, Jennifer M Jacobs, Wendy D Graham 2007. Relationships between military land use and storm-based indices of hydrologic variability. *Ecological Indicators,* 7: 553–564.

Brakensiek DL 1967. Kinematic flood routing. *Transactions of the American Society of Agricultural Engineers,* 212-232.

Bruijnzeel LA 2004. Hydrological functions of tropical forests: not seeing the soil for the trees. *Agriculture, Ecosystems and Environment*, 1-44.

Calder IR, Newson MD 1979. Land use and upland water resources in Britain-a strategic look. *Water Reourc Bull*, 16: 1628-1639.

Darcy H 1856. *Les Fontaines Publique de la Ville de Dijon*. Paris: Victoria Dalmont.

Gadgil M, Meher-Homji VM 1990. Ecological diversity. In: JC Daniel, JS Serrao (Eds.): Conservation in Developing Countries: Problems and Prospects. *Proceedings of the Centenary Seminar of the Bombay Natural History Society*, Bombay Natural History Society and Oxford University Press, Bombay, pp. 175-198.

Gash JHC 1979. An analytical model of rainfall interception by forests. *Quart J R Met Soc*, 105: 43-55.

Gash JHC, Wright IR, Lloyd CR 1980. Comparative estimates of interception loss from three coniferous forests in Great Britain. *J Hydrol*, 48: 89-105.

GWEM 1997. *Groundwater Resource Estimation Methodology: Report of the Groundwater Resource Estimation Committee*. Ministry of Water Resources, Government of India, New Delhi.

Homes RM 1961. Discussion of a comparison of computed and measured soil moisture under snap beans. *J Geophys Res*, 66: 3620-3622.

Horton RE 1933. The role of infiltration in the hydrologic cycle. *Transactions of the American Geophysical Union*, 14: 446–460.

Karthick B, Ramachandra TV 2007. Spatial variation of physico-chemical and hydrological parameters with land-use in Venkatapura catchment, Karnataka. *Asian Jr of Microbiol Biotech Env Sc*, 9: 981-985.

KSG (Karnataka State Gazetter) 1975. *Shimoga District*. Govt. of Karnataka.

Kumar R, Ramachandra TV 2005. Water, soil and sediment investigations to explore the status and management options of aquatic ecosystems. In: TV Ramachandra, N Ahalya, Rajasekara Murthy (Eds.): *Aquatic Ecosytems – Conservation, Restoration and Management*. New Delhi: Capital Publishing Company.

Lambin EF, Helmut J Geist, Erika Lepers 2003. Dynamics of land use and land cover change in tropical regions. *Annu Rev Environ Resour*, 28: 205-241.

Lillesand TM, Kiefer RW 2002. *Remote Sensing and Image Interpretation*. New York: John Wiley and Sons, Inc.

Lloyd CR, Marques Adeo 1988. The measurement and modelling of rainfall interception by Amazonian rainforest. *Agricultural and Forest Meteorology*, 343: 277-294.

Monteith JL 1965. Evaporation and environment. In: GE Fogg (Ed.): *The State and Movement of Water in Living Organisms: Symposium of the Society of Experimental Biology*. New York: Academic Press, pp. 205–234.

Penman HL 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of Royal Society*, 193: 120–145.

Putty MRY, Prasad R 2000. Understanding runoff processes using a watershed model- a case study in the Western Ghats in South India. *J Hydrol*, 228: 215-227.

Raghunath HM 1985. *Hydrology – Principles, Analysis and Design*. New Delhi: Wiley Eastern Limited.

Ramachandra TV, Bharath H Aithal, Durgappa DS 2012. Insights to urban dynamics through landscape spatial pattern analysis. *Int J Applied Earth Observation and Geoinformation*, 18: 329-343.

Ramachandra TV, Joshi NV, Rao GR, Dhanpal G, Gururaja KV, Yadav Amit S 2014a. Ecological status of three micro watersheds in Western Himalaya. *Indian Forester* (Special Issue on Himalayan Ecology and Biodiversity), 140(4): 331-347.

Ramachandra TV, Meera DS, Alakananda B 2013c. Influence of catchment land cover dynamics on the physical, chemical and biological integrity of wetlands. *Environment and We - International Journal of Science and Technology*, 8(1): 37-54.

Ramachandra TV, Nupur Nagar, Vinay S, Bharath H Aithal 2014b. *Modeling Hydrologic Regime of Lakshmanatirtha Watershed, Cauvery River*. IEEE-GHTC-SAS 2014, Trivandrum, Kerala, India.

Ramachandra TV, Subash Chandran MD, Joshi NV, Bharath Setturu 2013b. Land Use Land Cover (LULC) dynamics in Uttara Kannada Central Western Ghats. *Sahyadri Conservation Series 28, ENVIS Technical Report 56*, ENVIS, Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560012.

Ramachandra TV, Subash Chandran MD, Joshi NV, Karthick B, Vishnu D Mukri 2015. Ecohydrology of lotic ecosystems of Uttara Kannada, Central Western Ghats. In: M Ramkumar, K Kumaraswamy, R Mohanraj (Eds.): *Environmental Management of River Basin Ecosystems*. Heidelberg: Springer-Verlag, (In Press).

Ramachandra TV, Subash Chandran MD, Joshi NV, Vinay S, Bharath HA, Bharath Setturu 2013a. Carrying Capacity of River Basins Considering Ecological and Social Demands, *Sahyadri Conservation Series 36, ENVIS Technical Report 66*. CES, Bangalore: Indian Institute of Science.

Ramachandra TV, Subhash Chandran MD, Sreekantha, Diwakar Mesta, Rao GR, Sameer Ali 2004. Cumulative impact assessment in the Sharavathi River Basin. *International Journal of Environment and Development*, 1(1): 113-135.

Ray R, Subash Chandran MD, Ramachandra TV 2015. Hydrological importance of sacred forest fragments in Central Western Ghats of India. *Tropical Ecology*, 56(1): 87-99

Rutter AJ, Kershaw KA, Robins PC, Morton AJ 1971. A predictive model of rainfall interception in forests. I: Derivation of the model from observations in a plantation of Corsican Pine. *Agricultural Meteorology*, 9: 367–384.

Saint-Venant de Barre 1871. Theory of unsteady water flow, with application to river floods and to propagation of tides in river channels. *French Academy of Science*, 73: 148–154, 237–240.

Schmugge TJ, Kustas WP, Ritchie JC, Jackson TJ, Rango A 2002. Remote sensing in hydrology. *Advances in Water Resources*, 25: 1367-1385.

Schultz GA, Engman ET 2000. *Remote Sensing in Hydrology and Water Management*. Germany: Springer Verlag.

Scott DF, Lesch W 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *J Hydrol*, 199: 360-377.

Shuttleworth WJ 1989. Micrometeorology of temperate and tropical forest. *Phil Trans R Soc London B*, 324: 299-334.

Shuttleworth WJ 1993. Evaporation. In: DR Maidment (Ed.): *Handbook of Hydrology*. New York: McGraw-Hill.

Shuttleworth WJ, Calder IR 1979. Has the Priestly Taylor equation any relevance to forest evaporation. *J Appl Meteorol*, 18: 634-638.

Sikka AK, Samra JS, Sharda VN, Lakshman V 1998. Hydrological implications of converting natural grassland into bluegum plantation in Nilgris. *Bulletin - Central Soil and Water Conservation Research and Training Institute*, Dehra Dun, India.

Singh VP 1992. *Elementary Hydrology*. New Jersey: Prentice Hall.

Skidmore A 2002. *Environmental Modelling with GIS and Remote Sensing*. London: Taylor and Francis.

Turc L 1961. Evaluation des besoins en eau d'irrigation, evapotranspiration potentielle formule climatique simplifice et mise a jour. *Ann Agron*, 12: 13-49.

Turner BL, Meyer B 1994. Global land use and land cover change: An overview. In: B Meyer, BL Turner (Eds.): *Changes in Land Use and Land Cover: A Global Perspective*. New York: Cambridge University Press.

Van Lill WS, Kruger FJ, Van wyk DB 1980. The effects of afforestation with *Eucalyptus grandis* (Hill ex Maiden) and *Pinus patula* (Schlecht. Et. Cham.) on streamflow from experimental catchments at Mokobulaan. *Transvaal J Hydrol*, 48: 107-118.

Viessman WJr, Lewis GL, Knapp JW 1989. *Introduction to Hydrology*. 3rd Edition. USA: Harper and Row Publishers, Inc.